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**METHOD AND APPARATUS FOR
MANAGING ENERGY USAGE OF PROCESSORS
WHILE EXECUTING PROTOCOL STATE MACHINES**

5 BACKGROUND

1. Field of the Invention

Embodiments described herein are directed to a system for managing energy usage of processors while executing protocol state machines. Specifically, an alternate method of implementing protocol state machines that conserves energy on energy conscious devices is described.

2. Related Art

Protocol state machines typically represent communication protocol implementations. The actual implementation creates an instance of the state machine in a programming language such as assembler or C, for example. In addition, a protocol may involve communication between two entities such as two ends of a transport-level connection or two application level processes. In such a case, there must be multiple instances of the protocol state machine instantiated to handle separately the state and traffic involving each pair of separate entities engaged in the protocol-based communication.

Each such instance represents a separate and independent context and may have resources such as buffers, timers, etc. When a packet for the protocol is received, the context for the packet is identified; the corresponding instance of the protocol state machine is invoked; the instance executes the relevant part of the protocol state machine and returns to a dormant state until invoked again. On the transmission end, a separate instance of the protocol state machine handles each context. When invoked, the protocol state machine handles transmission of packets by performing necessary actions such as buffer management, setting a timer if the transmission

needs to be scheduled for a later time, and invoking the underlying protocol layer or physical hardware to complete the transmission. The transmit portion of the protocol may become dormant again.

Many parts of the protocol state machine require use of resources such as CPU cycles, memory, and timers. For instance, CPU cycles are necessary for execution of protocol state machine code or associated actions. Memory is needed for copying buffers and adding or modifying headers to packets. A timer may be set to schedule a transmission or retransmission, meter incoming traffic, or detect communication problems.

Typically, communication architectures are layered in two or more layers with a separate protocol handling the communication between peer entities at each layer. Traditional protocol state machine implementations use single or multiple threads to represent and execute multiple contexts that represent multiple instances of a protocol state machine. At any time, a myriad of such instances may execute depending on the number of protocol layers and the number of concurrently communicating entities on a given machine.

Each of these instances uses the resources that it needs at any given time, depending on the incoming or outgoing traffic. Therefore, a snapshot over any interval shows frequent use of resources at irregular intervals followed by intervening idle or dormant periods. This does not pose any particular problem on a conventional machine. Such a frequent but irregular use of resources, however, can cause a significant drain of energy on a new class of devices such as handheld computers, wireless devices, or embedded devices. Power is a critical resource on such devices. Each time that a timer goes off or memory is accessed, additional energy consumption is required. In addition, frequent cycles of dormant versus active states at irregular intervals interfere with the power management schemes used on such devices that attempt to conserve energy by “turning down” unused resources during idle times. As such, an alternate method of

implementing protocol state machines that will conserve energy on energy conscious devices is necessary. That is, an incremental method of distributing energy usage away from disruptive and irregular patterns to a more predictable and cooperative pattern that can be exploited to reduce overall energy usage would prove advantageous.

5 **BRIEF DESCRIPTION OF THE DRAWINGS**

A detailed description of embodiments of the invention will be made with reference to the accompanying drawings, wherein like numerals designate corresponding parts in the several figures.

FIG. 1 is a block diagram that illustrates management of energy usage for one transmitting protocol state machine and one receiving protocol state machine, according to an embodiment of the present invention.

FIG. 2 is a block diagram that illustrates management of energy usage for a multiple protocol layer/multiple protocol state machine scenario, according to an embodiment of the present invention.

FIG. 3 is a flow chart that illustrates the actions taken by a transmitter protocol state machine in the overall system of managing energy usage of processors, according to an embodiment of the present invention.

FIG. 4 is a flow chart that illustrates the actions taken by a receiver protocol state machine in the overall system of managing energy usage of processors, according to an embodiment of the present invention.

DETAILED DESCRIPTION

The following paragraphs describe a method and apparatus for managing and conserving energy usage of processors on energy conscious devices while executing protocol state machines. Under this method, most of the energy consuming protocol state machine

instance/context invocations or operations are aggregated in time and are scheduled at regular intervals. Such an aggregation leads to multiple instances or contexts executing concurrently in a burst before entering a dormant state. Therefore, resource usage can reach a predictable pattern of idle and active cycles.

5 With such a pattern, it is possible to take advantage of the energy saving features of processors by downshifting processor clock speed and use of other resources such as peripherals and buses. The intervals are configured to achieve a tradeoff between timely execution and energy consumption. The aggregation operates across two dimensions, namely, across multiple instances of a protocol state machine and across multiple layers of protocols in a layered architecture.

Figure 1 illustrates a single instance of managing energy usage by implementing a single protocol state machine. That is, one transmitter protocol state machine **110** and one receiver protocol state machine **120** are employed. The transmit protocol state machine **110** is tasked with sending a set of packets **130** to another host over a data communication network **140**. The data communication network **140** may be the Internet, an intranet, or any other kind of public, private, or other data communication network. Packets **130** are pieces of information or data that is divided into segments. The transmit protocol state machine **110** then waits for these packets **130** to be acknowledged by the receiving protocol state machine **120** before transmitting the next set of packets **130**. This is a typical algorithm for the reliable transport of packets **130** over an unreliable data communication network **140**.

The transmitter begins in a high powered, high clock rate mode. High means greater than low. This is illustrated as step **310** in Figure 3. As shown in step **320**, the transmitter then invokes the protocol state machine **110** to transmit packets **130** periodically. Starting with raw data, the transmit protocol state machine **110** performs tasks to create packets **130** for

transmission, such as dividing the raw data into packets **130**, adding protocol headers, and computing checksums. The transmit protocol state machine **110** sends these packets **130**, as shown in step **330**, and waits for acknowledgments from the receiver protocol state machine **120**. While waiting, the transmitter protocol state machine **110** switches into a low power, low clock rate mode, as illustrated in step **340**. While waiting, the transmitter protocol state machine **110** does not wake up to handle every incoming acknowledgment. Instead, it wakes up only when a timer sounds or when an incoming packet buffer reaches a low water mark, as shown in step **350**. The transmitter then prepares for the sending of additional packets **130**.

The receiver protocol state machine **120**, in contrast, starts in a low power, low clock rate mode, as shown in step **410** of Figure 4. When packets **130** are received from the data communication network **140**, they are simply buffered, as illustrated in step **420**. Step **430** examines whether a buffer has reached a maximum capacity or a high water mark. If such a threshold has not been reached, the receiver protocol state machine **120** returns to step **410**. When the buffer is full or reaches a high water mark, the receiver protocol state machine **120** is invoked, as illustrated in step **450**, after switching to a higher powered, higher clock rate mode, as shown in step **440**. In this scenario, the frequency and power level of the processor is driven by the received or transmitted data. The packets **130** are processed by the receiver protocol state machine **120**, and acknowledgments are sent to the transmitter protocol state machine **110**, if required by the state machine. When the processing of packets **130** is complete, the receiver protocol state machine **120** returns to an idle state, as depicted in step **410**. The use of buffers and timers in both the transmitter protocol state machine **110** and the receiver protocol state machine **120** results in periodic patterns in data reception and transmission. The periodicity may then be used to manage the power and frequency settings of the host processor.

Figure 2 illustrates an instance of managing energy usage in the multiple protocol layer, multiple protocol state machine scenario. Transmission Control Protocol ("TCP") **240** (shown also as **240'**) [Transmission Control Protocol, Request For Comments ("RFC") 793, published September 1981] and Internet Protocol ("IP") **250** (shown also as **250'**) [Internet Protocol, Request For Comments ("RFC") 791, published September 1981] are used only as examples, for the technique may be applied to other transmission protocols and other scenarios. TCP **240** is an agreed upon format for transmitting data between two devices. TCP **240** provides end-to-end, connection-oriented, reliable transport layer (layer 4) functions over IP **250** controlled networks. Typically, TCP **240** performs flow control between two systems, acknowledgments of packets received, and end-to-end sequencing of packets. IP **250** operates in conjunction with TCP **240** and is usually identified as TCP/IP. IP **250** is a connectionless protocol that operates at network layer (layer 3) of the Open System Interconnection ("OSI") model, a seven layer architecture model for the interconnection of data communications systems [Open Systems Interconnection model, ISO/IEC 7498, published 1994]. Each layer uses and builds on services provided by those below it. The OSI model creates an open systems networking environment where different systems can share data regardless of vendor or platform.

Similar to the previous instance, the receiver TCP protocol state machines **230a** and **230b** (pictured also as **230a'** and **230b'**) begin in the low power, low clock rate mode. In this state, packets **130** received from the data communication network **140** are buffered. When this buffer is full or reaches a threshold, the host switches to a higher clock rate, higher power mode. The Internet Protocol **250** layer is then invoked and processes the buffered packets **130**. These packets **130** are demultiplexed and delivered to separate instances of TCP protocol state machines **230a** and **230b**. Each TCP protocol state machine **230a** and **230b** maintains the state of a unique end-to-end connection. The TCP protocol state machines **230a** and **230b** process the

packets **130** and store the raw bit stream in application provided buffers, namely APP1_buff **220a** (shown also as **220a'**) and APP2_buff **220b** (pictured also as **220b'**). Two application buffers are shown for illustration purposes only. In reality, a great many application buffers may be employed. When the total number of packets **130** in all application buffers reaches a

5 threshold or when an application buffer reaches capacity, the processor is switched to a different clock mode and power level to execute application code. This mode may be higher or lower depending on the application's requirements.

The transmitter starts by running at an appropriate clock rate for the particular application, APP1 **210a** (also **210a'**) or APP2 **210b** (also **210b'**). APP1 **210a** and APP2 **210b** fill APP1_buff **220a** and APP2_buff **220b**, respectively. When either buffer **220a** or **220b** is full or when there is sufficient data in all of the buffers **220a-b**, the applications are blocked, and the TCP protocol state machines **230a** and **230b** are invoked to process the data in the buffers **220a** and **220b**. The transmitter switches the processor clock and power mode to an appropriate one for TCP **240** processing. The TCP protocol state machines **230a** and **230b** process the data and pass packets **130** to the IP **250** and Media Access Control ("MAC") **260** (shown also as **260'**)

10 15 layers. The MAC **260** layer transmits the data into the data communication network **140**. The MAC **260** layer operates at the data link layer (layer 2) that defines topology dependent access control protocols for local area network specifications.

While the above description refers to particular embodiments of the present invention, it

20 will be understood to those of ordinary skill in the art that modifications may be made without departing from the spirit thereof. The accompanying claims are intended to cover any such modifications as would fall within the true scope and spirit of the present invention.

The presently disclosed embodiments are therefore to be considered in all respects as illustrative and not restrictive; the scope of the invention being indicated by the appended claims,

rather than the foregoing description. All changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

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